The Role of Design in Product Innovation: Design Ergonomics and the Development of the Portable Computer

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Abstract

The paper discusses the strategic importance of design in product innovation. Technological downscaling in microprocessors and storage media has decoupled the design and ergonomic features (size, weight, and user interfaces) of consumer electronic products from these technologies. Competitive advantage and product innovation focuses on the development of design frames that embody specific sets of design and ergonomic characteristics, as well as technical characteristics. Our study of portable computers highlights the role played by the clamshell design frame in driving the trajectory of product innovation in that sector. Statistical analysis is performed on a data set of portable computer characteristics for the period 1993 to 1997. Using principal components analysis we identify distinct sets of ergonomic and technology characteristics. Hedonic price models are estimated using these clusters. The findings indicate that long term success depends on the strategic harnessing and integration of inputs from designers and R&D engineers within the product innovation process.

Keywords: product innovation, design, hedonic prices, portable computers.
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INTRODUCTION

The objective of this paper is to critically re-address our understanding of product innovation by viewing innovation from a design services perspective. Product innovation is an extensively studied field - the vast majority of manufacturing case studies concern product innovation. Yet the focus has been overwhelmingly on the technological contribution to innovation. We draw attention to the fundamental role of design frames and the activities of designers in product innovation. Design choice determines the set of feasible technology options and the trajectory of product innovation.

The paper introduces the concept of design frames. Design frames are solutions to specific problems, which may be used and re-used in a number of different contexts. Occasionally, radically new design frames are invented in order to tackle technical, ergonomic and/or aesthetic problems which existing design frames fail to solve. We apply Dosi’s (1982) work on paradigms and trajectories to understand the choices made by designers within the innovation process, and how these choices focus product innovation on particular trajectories. Designers share a common set of practices and a repertoire of design frames, and apply these to daily problem solving. Through trial-and-error experimentation, new design knowledge is developed and communicated to other design practitioners, through the artifacts solutions they develop and through an extensive range of publishing media which include specialist design magazines, research journals, books, and internet websites. Designs frames focus the innovative activities of practitioners along specific trajectories of product development, both in terms of the new/improved features which are developed, and the types of technology which are applied.

The second contribution of the paper is an empirical application of these concepts to the portable computer. The clamshell portable computer was a radically new design frame with a distinct set of core design and technical characteristics. Market selection of this design frame, from a number of competing alternatives, placed the sector on a very specific trajectory of product innovation. Product innovation has focused on developing the inherent strengths of this design frame and simultaneously addressing its weaknesses. The commercial success of individual clamshell models is predicated on a balancing of interactions between technology features and ergonomic features.
We examine the characteristics econometrically with a data set containing the ergonomic and technical characteristics of clamshell portables produced between 1993 and 1997. First, hedonic price regressions are estimated for the individual characteristics. Then principal components analysis is applied to explore the structure of interactions between these design and technical characteristics. Two distinct clusters are identified: a cluster of ergonomic characteristics and a cluster of technology characteristics. Hedonic models are estimated using these distinct clusters in order to identify the shadow prices which consumers are willing to pay.

EXISTING THEORIES OF PRODUCT INNOVATION

A well established body of theoretical and empirical research exists on the development of technological innovation and competition. Founding works include Abernathy & Utterback (1975), Nelson & Winter (1982), Rosenberg (1982), Dosi (1982), Saviotti & Metcalfe (1984), Porter (1985), and Henderson & Clark (1990). With respect to products, the characteristics approach is commonly used to analyze and categorize different types of product innovation. A product is described in terms of a list of features, or ‘characteristics’. This enables one to distinguish between product innovations that improve the quality of one characteristic, innovations which improve the quality of multiple characteristics, and innovations that involve the introduction of completely new characteristics (Swann 2009).

Characteristics Approach

Kelvin Lancaster (1966, 1971) observed that all types of products (both manufactured goods and immaterial services) can be described by the bundle of attributes, or ‘intrinsic characteristics’, which they embody. Characteristics are the stream of services, provided by a good/service, which the buyer consumes over the lifetime of the purchased product. Differences in the demand prices of rival products reflect differences in the quality of the intrinsic characteristics from which consumers derive utility.

Lancaster (1971) illustrated the characteristics approach using the example of the electric kettle. The quality of the intrinsic characteristics of an electric kettle depends on both its design ergonomics and its technical performance. Consumers derive more utility from certain types of kettle design than others due to
heterogeneous preferences with respect to the aesthetics of different kettle designs (how they look, including the type of materials from which they are made – plastics, metal, etc.), their ergonomics (how well the kettle balances in the hand when lifted and is full of water), and the ease of use and maintenance. Other characteristics, such as how quickly a given volume of water can be boiled and its energy efficiency, depend on the technical features of a kettle design. In an electric kettle this is determined by the size of the electric element and the materials of which the element is made.

Paolo Saviotti and Stan Metcalfe (1984) took Lancaster’s work and developed a model of technological innovation. Their focus is narrower than that of Lancaster. The Saviotti & Metcalfe framework identifies a set of ‘service characteristics’ from which consumers derive utility through consumption. The quality of these service characteristics are said to depend on an underpinning set of core technologies whose performance can be described by a vector of ‘technical characteristics’. Improvements in technical characteristics, achieved through R&D, enhance the quality of the associated service characteristics that are of interest to consumers.

**Paradigms and Trajectories**

The Saviotti-Metcalfe framework is operationalized using Giovanni Dosi’s (1982) theory of technological paradigms and trajectories (see Saviotti 1996). Dosi took Kuhn’s concepts of ‘scientific paradigm’ and ‘shared communities of practice’ based on a common set of learned heuristics and tools (Kuhn 1962), and applied it to the study of how engineers operate in R&D labs. Dosi defines a technological paradigm as a “‘model’ and a ‘pattern’ of solution of selected technological problems based on selected principles derived from natural science and selected material technologies” (Dosi 1982, p. 152).

For Dosi, a technology is “a set of pieces of knowledge both directly ‘practical’ (related to concrete problems and devices) and theoretical (but practically applicable although not necessarily already applied), know-how, methods, procedures, experience of success and failure and also, of course, physical devices and equipment” (Dosi 1982, p. 151). A ‘technological trajectory’ is the pattern of ‘normal’ problem solving activity (the parallel of Kuhn’s ‘normal science’) that seeks incremental performance improvements based on the existing set of accepted technical frames and solutions. By contrast, a radical innovation is founded on the
creation of a new set of technological solutions, and results in a new trajectory that is qualitatively different to the old technology trajectory. This may initially be sparked by the incremental development of a technology. As engineers seek to improve the performance of a product, they realize the need to engage in a radical redesign of the core technologies and/or the sets of core technologies that are used in the product. This can lead to a new set of conceptual models and solutions, thereby establishing a new paradigm with a new technological trajectory.

**Econometric studies**

One finds in the econometric studies an almost exclusive focus on the technological aspects of product innovation. This is noticeable in a wide range of product studies that include automobiles (Saviotti 1985), helicopters (Saviotti & Tricket 1993); computed axial tomography (CAT) scanners (Trajtenberg 1989), spreadsheet software data (Swann 1993), bio-diagnostic kits and capital goods data (Grupp 1998), and civil aircraft (Frenken & Leydesdorff 2000). What is striking about these studies is their singular focus on technical characteristics, such as the speed and thrust of jet engines, the clock speeds of microprocessors, and so on.

A direct consequence of this technological focus is a lack of research on the role of design in product innovation, and the relationship between technical characteristics and the design characteristics which define the form and function of a product, and its ergonomics. As Tether (2006) puts it, there is a need to bring design out of the shadows of R&D.

**Upscaling and downscaling**

We propose that ergonomic and technical characteristics may interact to a lesser or greater extent in different categories of products. In products such as aeroplanes and automobiles, the direction of product development is related to a set of underpinning technologies – notably, the size, weight and thrust of engines designs, the aerodynamics of body shape, and the weight and strength of the materials used to build the bodies of aeroplanes and automobiles. The development of long range commercial passenger aircraft since the 1950s saw the upscaling of propeller engines followed by the development of more efficient turbofan engines. Similarly, the development of more powerful and faster cars required the upscaling of internal combustion engines (Nelson & Winter 1977).
By contrast, the ergonomic characteristics of many electronic consumer products – i.e., their size, weight, shape, and how they interact with the human body – are not governed by an underlying set of technological factors or constraints. The technological trajectory is one of miniaturization, or ‘downscaling trajectory’ thanks to ongoing improvements in microchip technology and disk drive technology combined with the digitization and compression of music, video and still images through, for example, MP3, AVI, and JPEG codings. Since the early 1960s, computing power has doubled every 18 months in line with Moore’s Law.\(^4\) By shortening the path that an electron needs to travel, the process of miniaturization on integrated circuit boards improves clock speed (i.e. the rate at which a transistor switches on and off) (Swann 1986). The size and weight of electronic devices are no longer dependent on the size of microprocessors. Christensen (1993, 1997) discusses a parallel trend in disk drives. Indeed, the rate of increase is greater than that the rate of improvement in microprocessor capacity. When IBM invented the first computer disk storage system, the 305 RAMAC (Random Access Method of Accounting and Control) in 1956, it comprised fifty 24 inch diameter disks with a maximum storage capacity of 5 Mbytes. In 2007, Hitachi introduced the Deskstar 7K1000, the first 1 terabyte 3 ½ inch disk drive. It is this ongoing increase in the density of information on hard drives which facilitates improvements in microprocessors.

This downscaling technological trajectory has progressively relaxed the technical constraints on the design and ergonomics of electronic consumer durables, opening up greater degrees of freedom for designers. Consequently, one must examine design characteristics and the contribution of designers to product innovation if one wishes to understand competitive advantage and innovation trajectories in products such as portable computers, mobile phones, MP3 players, portable DVD players, and games consoles (e.g. Wii, Nintendo DS, and Playstation).

The remainder of this paper focuses on the role that design has played in the development of portable computers. This is of interest because the portable computer was the first portable, digital media consumer product. Also, the portable computer sector conforms with many of the stylized facts of the industry life cycle discussed by

\(^4\) Moore (1965) observed that technical improvement in computer design over the previous 20 years had resulted in a doubling of processing power approximately every 18 months. Extrapolating, Moore (correctly) predicted that, in order maintain this rate of exponential growth, the number of components on an integrated circuit board would need to increase from \(2^6\) components to \(2^{16}\) components over the following 20 years. Indeed, ongoing R&D in chip manufacture and the advent of parallel processing have enabled circuit manufacturer to maintain this rate of increasing processing power to this day.
Klepper (1996). Insights in this sector potentially have a wider applicability to other consumer electronics sectors in which there has been technological downscaling.

**THE DESIGN COMMUNITY**

We apply Dosi’s work on paradigms and trajectories in order to study the choices made by designers, and to appreciate how these choices lead product innovation to be focused along certain trajectories of development rather than others. The contributions of design to product innovation can be classified under three main categories: technical, ergonomic, and aesthetic (Brown 2008, Press & Cooper 2003). The technical contribution of designers is connected, in a fundamental way, with problem-solving. For example, designers engage in translating a perceived ‘need’ into a ‘product concept’. To do this they create or assemble existing parts / components of a device or artifact (ensuring that these can be connected or aligned in an appropriate way, and inserted into an appropriate housing), they select appropriate materials, and create context-appropriate user-interfaces. Beyond this, the technical contribution of the designer is frequently required whenever a firm needs to ensure compliance with existing standards, safety or environmental regulations, or where guidance is needed with respect to prototyping or the manufacturing process.

With regards to ergonomics, designers need to address the product’s ease of use, and the comfort of consumers who are expected to interact with it. The planning and design of user interfaces and the creation of devices and environments that take into account the physical and sensory characteristics (and sometimes limitations) of likely users is a core role for the majority of product and industrial designers. Indeed, ‘ergonomy’ has become as a specialized sub-discipline within design.

The realm of aesthetics is one in which art meets cultural codes, fashion and style, and it is here that the designer is challenged to create designs that deliver both practical functionality and attractiveness vis-à-vis an individual user or a group. The key contribution of the designer is the creation of products that work well and look good (or at least convey a desired message about the user of a particular product in a specific setting), and products that are differentiated from competitors in any given market space. However, aesthetic considerations stretch well beyond the styling of individual artifacts. Designers are increasingly called upon to assist in the planning (or redesign) of product ranges, the reinforcement of brand identity, and the embedding of brand values.
Clearly, there are many ways in which the activities of designers affect the trajectory of product innovation. Radical design innovations may occasionally trigger an entirely new innovation trajectory. Similar ideas to Dosi’s concepts of paradigms and problem-solving heuristics (though nuanced by the specific characteristics of designers and design activity) can be found in the research literature on design. There is a focus on the particularities and transitions of design practice, and an analysis of continuity and change in design methodologies, cultures, processes and products. Specifically, scholars highlight three related themes: key trends in design systems and ideology; the concepts of the ‘design career’ and ‘expert designer’; and, the evolution and application of design methodologies and tools.

There has been a deliberate and consistent attempt within the design community to forge a professional culture, mindset, and a toolkit to underpin design activity. This began in the 1960s, with a modernist movement that sought to ‘scientize’ design endeavor (Cross 2001). Led by high-profile design theorists such as Christopher Alexander, J. Christopher Jones, and Stephen Gregory, proponents advanced the idea that the design process and its products should be radically refigured to conform to the principles of logic, rationality and objectivity (Fuller 1999, Hubka 1982, Pahl & Beitz 1984). By deriving and applying a set of governing principles and methods, it was argued, designers could remove the uncertainty that had hitherto characterized design outcomes, and surmount the socio-environmental problems that politics (invested as it is with sectional interests and subjective analyses) could not hope to address.

The scientization movement succeeded in developing a distinct ‘world view’ and a set of generalizable heuristics for problem-solving. The 1970s saw a shift away from a belief in a universal set of practices to a more nuanced appreciation of the particularities of design in different contexts. This recognized the way in which certain heuristics are intuition-based and can be culturally specific. The reaction to the scientization project did not indicate the absence of shared culture or approach in the design world. Rather, it highlighted the need for a more profound reading of the subtleties and nuances of the protocols and cognitive orientations that guide design practice (Cross 2001).

Scholars have investigated the procedures and toolkits that are deployed by designers in the day-to-day execution of a project (Walker 1993, Sonnenwald 1996). Petre (2004) provides a comprehensive review of the approaches and tools that are
used by design engineering consultancies in the US and UK. He identifies fourteen factors, ranging from knowledge capture to scenario building and experimentation, which are successfully applied by top performing firms. The systematic application of tested instruments, methods and procedures appears to be correlated strongly with success. The study also notes an organic and dynamic quality to the ‘best’ design firms - tools are constantly adapted and updated in the light of project experience. Those responsible for their deployment are frequently involved closely in the process of enhancement or re-design.

There is a clear and strong resonance here with Dosi’s discussion of engineers’ use of heuristics to solve technological problems. While the practices and heuristics used by designers and engineers differ, it is striking is that each community utilizes a set of systematized practices (common tools, materials, methods and applications), incrementally builds upon these practices through trial-and-error experimentation, and communicates new knowledge to their respective communities. In the case of the design community, new product knowledge is communicated through the artifacts which they develop, and through an extensive range of publishing media – specialist design magazines, research journals, books, and internet websites.

Schon (1984), Schon & Wiggins (1992), and Ericsson, Krampe & Tesch-Romer (1993) examine the career path which aspirant design professionals follow to achieve accreditation and, more importantly, the credibility that permits them to ascend from novice to expert designer. Whilst there are several configurations of the novice-expert career path (Lawson 2006, Atman, Chimka, Bursic & Nachtmann 1999), some common themes can be distilled. The most important skills and qualities to be acquired by aspirant designers relate to (a) the recognition and (re-) framing of design problems, (b) the identification of feasible solutions (founded in boundary-spanning and abstract thinking), (c) the development of solution ‘gambits’ (Lawson, 2004), and (d) the deployment of experience-based intuition. Formal education and informal professional induction involves a very significant degree of enculturation; in effect, the immersion of the inductee into a specific way of ‘knowing’ (Schon 1988, Cross 2001, Petre 2004). This parallels Dosi’s discussion of the education of engineers in universities and specialized schools followed by hands-on experience (working closely with colleagues) in innovation projects in R&D departments.

In the next section we introduce the concept of a ‘design frame’ – an important problem-solving heuristic device – and the ‘balanced product’ concept. This paves the
way for a discussion of the clamshell computer design frame and how its introduction focused innovation on a specific product development trajectory.

**DESIGN FRAMES and BALANCED PRODUCTS**

We define a design frame as a particular design solution that addresses a specific problem. ‘Normal’ problem-solving activity in the world of industrial design is founded on a repertoire of design frames which are used, re-used, and developed over time. Associated with these design frames is a specific set of cognitive orientations, routines, practices, and associated tools, materials, methods and applications. A radically new design frame may be developed to tackle technical, ergonomic and/or aesthetic problems that previous design frames fail to solve. If successful, the new solution may be subsequently applied in other product domains. When this occurs, a design frame becomes part of the common repertoire of frames used by the design community.

In the case of the portable computer, the clamshell design frame was developed to tackle the problem of providing a useable portable computer with sufficient computing power, at an affordable price, that would enable the earliest adopters of sales people and middle managers to run spreadsheet software and word processing and software with clients away from the office.

Three alternative design frames were initially developed: the clamshell, the portable box, and the tablet. Each had its strengths and weaknesses. Market convergence to the clamshell design frame focused product innovation on a particular path, or ‘trajectory’. Producers sought to improve the inherent strengths of this design frame while simultaneously tackling its inherent weaknesses.

This focusing of innovation is broader in scope than Thomas Hughes’ (1987) discussion of performance bottlenecks (or ‘reverse salients’). Overall improvement in technical performance may be limited by a bottleneck in one of the components or subsystems that make up a product. Hughes observed that innovative attention tends to focus on resolving the bottleneck. While it is undoubtedly correct that a major bottleneck will focus attention until it is resolved, we propose that innovative activity is more generally guided by the set of strengths and weaknesses that are inherent in a particular ‘design frame’.

The design frame concept is closer to Henderson & Clark’s (1990) notion of ‘architectures’ that determine the way “in which the components of a product are
linked together” (Henderson & Clark 1990, p.10). A design frame not only determines the particular set of components that are used in the first examples of a new product, it directs the path of future component innovation. Understanding the direction which design frames impart to innovation trajectories helps us appreciate why the trajectories of the clamshell portables differ to the personal computer (PC), for example. The basic problem facing PC designers is between the trade-off price and the demand for higher computing speed and disk drive storage. Portability and ergonomics are not binding constraints for the designers of desktop PCs.

Within a given design frame, designers seek to develop a ‘balanced product’ that meets the preferences of consumers. As we shall see, in the case of the clamshell frame this involves balancing trade-offs amongst two sets of interrelated variables. One set is the design/ergonomic criteria involved in producing a large screen with sufficient battery power to run the screen for a usable period of time away from mains power access, and an integrated base unit that houses the keyboard user interface and the computing hardware.

Balance is also required in the development of the microprocessors and disk drives used in portable designs. Computing power is a complex phenomenon that governs both computer speed and software stability. Strong interactions exist between the technical characteristics of processor speed, RAM, and hard disk drive capacity. These interactions result in a second dimension in which the needs of a balanced design place innovation on a specific trajectory of development. Developing a balanced product requires designers to address both interactions within each set of interrelated variables.

**DEVELOPMENT OF PORTABLE COMPUTERS**

The clamshell was a radical design innovation that became the standard ‘form factor’ for portable computers. It has been subsequently applied to many other portable products, such as mobile phones, cordless phones, portable DVD players, and portable games consoles (e.g. Nintendo DS and Game Boy).

The clamshell design was developed by Bill Moggridge, a leading British industrial designer, in association with GRiD. The design was patented (U.S. Patents D280,511 and 4,571,456) for the GRiD Compass portable computer, which was launched in April 1982. The design is a ‘form factor’ – it comprises two sections that fold via a hinge. The components are kept inside the clamshell, and opened up when
in use (Figure 1). The GRiD Compass introduced many novel product characteristics that are now standard. It sported a large, flat panel (monochrome) electroluminescent display screen that had been developed by Jim Hurd of Planar Systems. It had an Intel processor, large RAM and data storage memories, a modem, user accessible voltage conversion, and battery power capability. These components were housed in a rectangular magnesium case, designed to ensure high levels of component protection and an efficient heat dissipation mechanism. The Compass weighed 11 lbs (Wilson 2006).

The clamshell was one of a number of competing design configurations that existed in the 1980s. The first commercially successful portable computer was a ‘portable box’ design, the Osborne I, released in April 1981 (Figure 1). It had a CP/M operating system, and was shipped with pre-loaded spreadsheet, database, and word processing software. Portable box computers are often referred to as a ‘luggables’ due to their relatively large size (about the size of a small suitcase) and weight. The Osborne I was housed in large and rather heavy plastic box (20 ½ inches wide, 14 ½ inches deep, and 8 ½ inches high) that weighed almost 24 lbs. The unit opened on one side to reveal a 5 inch monochrome cathode ray tube (CRT) display and a fold-down keyboard. The Osborne I featured just 64 kilobytes of RAM and incorporated a modem, two 5¼ inch floppy disk drives, one placed on either size of the small CRT screen. There was an optional battery pack. Transportable box computers were produced by a number of companies. Models included the Kaypro 10 (1983), IBM Portable PC (1983) which was portable box version of the PC XT, Access Matrix Corporation Actrix DS (1983), Compaq Portable (1983), IMC Traveller286 (1984), Kaypro 4 (1984), Philips P200C (1984), Zenith Z-171 (1985), Amstrad PCC640 (1988), and the IBM PS/2 P70 386 (1989).

The tablet computer was a third design frame. The first commercially available tablet-type portable computer was the GRiDPad 1910 (Figure 1), launched by GRiD in September 1989. It had a 80C86 chipset and came with 1MB RAM. It measured

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5 This predates the IBM PC (5150) which was launched in August 1981 in the US.
9x12x1.4 inches with a 640x400 screen, and weighed 4½ lbs (around three-quarters of the weight was due to the screen and its magnetic position sensing system). The key distinguishing feature of tablets is that they dispense with the QWERTY keyboard. The tablet is a large touch-sensitive screen (typically A4 / `standard' letter sized) covering a processor unit. Handwriting recognition capabilities allow information input via a pen or stylus (Atkinson 2008). Some firms also experimented with more expensive ‘hybrid tablets’, such as the Compaq Concerto (1992). These are hinged folding designs that include a keyboard, rather like the clamshell computer. However the tablet differs to a clamshell in that all the hardware is placed in the screen while the keyboard is the lighter part.

Early portables were expensive. When launched, the Osborne I cost $1800.00, the GriDPad 1910 cost $2370.00, and the GRiD Compass had a price tag of over $8000.00. The price of the Compass precluded widespread commercial sales and its use was largely restricted to the US military and NASA (the Compass was the first laptop to make its way into space). Compared to contemporary personal computers (PCs), the early portables had significantly lower technical specifications. Still, the benefits of mobility were sufficiently attractive to two types of lead user - field salespeople and senior executives. Given the bundling of applications software, users could, for the first time, carry spreadsheets, complete standardized electronic orders, and collect or log other information which could be used to update company databases upon their return to the office. There was also a certain cachet associated with the ownership of a relatively expensive and, hence, exclusive new technology product (Atkinson 2005).

Box, clamshell, and tablet designs have their relative strengths and weaknesses (Wilson 2006). The clamshell design had three distinct advantages. First, a significant surface area can be compactly stored when the device is closed. The dimensions of the clamshell design were shorter and narrower than portable box computers, making clamshells easier to carry around. The two key features of the clamshell design were the large sized screen and a full sized QWERTY keyboard. Box computers invariably had small sized CRT screens, while tablet computers dispensed with keyboards entirely. In the clamshell design, the QWERTY keyboard is on top of an integrated base that houses all the hardware (microprocessor, disk drives, cooling fan, printer ports and other external device interfaces). The second advantage of the folding clamshell design is the protection it affords interface components, such as keys and
display, when it is closed. The third advantage is its ergonomics. The size and compactness of the design means it can be balanced on the lap of a seated user. Placing the heavier components (battery, cooling fan, and disk drive) in the base unit and minimizing screen weight in the lid enhances stability in the user’s lap.

There are three relative disadvantages to the clamshell. Each is a consequence of the integrated base design. The first problem is effective thermal management. The low height of the integrated base makes it difficult to dissipate the heat generated by microprocessors. Second, the integrated base makes user upgrades difficult. Machines must be shipped back to the manufacturer for a hard disk upgrade, for example. Other types of upgrade, such as screens and ancillaries are simply not possible in this integrated design. Third, the compact space of base prevents the sourcing of the large disk drives and fans used in PCs, preventing scale economies and raising costs.

Box computers were large and heavy in comparison to clamshells but this offered some advantages. For a start, standard PC components could be used. Also, the greater volume of internal air combined with standard PC fans meant boxes did not suffer the thermal management problems of clamshells. The box computer, like the PC, was a highly modular design (Langlois & Robertson 1992) that could be easily upgraded by the consumer. The key disadvantage of the box computer was its size and weight. Its ergonomics were very poor, its weight preventing its use on the user’s lap. Also, it was not possible to physically carry a box computer for extended periods.

The strengths and weaknesses of the tablet computer lie in its dispensing with the QWERTY keyboard - its principle design aspect. Lighter weight, lower power models have found a niche in warehouse inventory, and in highly standardized form filling in hospitals, sales, and insurance work. They are not useful in more general applications where large amounts of text need to be entered (i.e. via a QWERTY keyboard). Hybrid tablet designs, such as the Compaq Concerto, were not as practical in use as clamshells. Having the weight in the screen meant they could not be balanced on the user’s lap. Further, the stress of the weight placed on the extendable legs used to prop up the screen made this a weak mechanical point prone, to breaking. Tablets are as limited as clamshells with respect to user upgrades. Tablets have recently been applied in other portable products, such as dedicated reading devices (e.g. the Amazon Kindle) and mobile phones (e.g. Apple iPhone). Apple’s recent
launch of the iPad – a tablet computer – may see the commercial reintroduction of
tablet portable computers.

The clamshell won this standards battle in the early 1990s and became the
dominant industry design (Abernathy & Utterback 1975). As in other product
markets, the emergence of a dominant design sparked a round of market entry.
Radical product innovation began apace as companies competed to produce powerful,
yet compact, clamshells. An industry shake-out occurred in the early 2000s. Product
innovation and strong competition led to a highly standardized set of characteristics
and competitive advantage shifted to large scale production and cost/price reduction.
As in other sectors (Klepper 1996), this shift precipitated a market shake-out.

The logic of the clamshell design frame fixed product innovation on a specific
trajectory of product innovation. Developing the strengths of the clamshell design
focused innovation along a particular path. Notably, the development of larger, higher
resolution screens, and the development of more powerful batteries to support these
higher quality screens. The GRiD Compass had used a large electroluminescent flat
screen display. Designers subsequently looked to other, more efficient screen
technologies. The Toshiba T1100 (released in April 1985) was first clamshell to use a
backlit liquid crystal display (LCD) screen.6 LCDs were particularly suited to the
clamshell design. They provided better resolution and luminosity than
electroluminescent screens, and their lightness and thinness was particularly suited to
their use in the clamshell lid. Further, the low electrical power consumption of LCDs
placed less demand on batteries than electroluminescent screens.

The commercial success of clamshell portables bootstrapped the development
of LCDs in the 1990s (Lien, Cai, John, Galligan & Wilson 2001). Thin-film transistor
liquid crystal display (TFT-LCD) panels began volume production in 1991. Early
LCDs had slow refresh rates which blurred the screen, even with scrolling text. This
was addressed by adding memory to hold before and after values in computer
memory, comparing them, and only resetting those sub-pixels that actually change.
The amount of time spent charging and discharging the capacitors was reduced,
further improving power efficiency.

In a similar fashion, the commercial success of clamshell portables
bootstrapped the development of batteries in the 1990s. Over-stressing a battery can

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6 An organic liquid is the active ingredient in an LCD panel; argon or neon gas in a gas plasma screen;
a metal film in an electroluminescent screen.
result in catastrophic meltdown.\textsuperscript{7} As larger screens placed increasing demands on battery power, so the nickel-metal-hydride (Nimh) battery, first introduced in the late 1980s, quickly replaced nickel–cadmium batteries. Nimh offered 30–40\% higher capacity over nickel–cadmium, was less prone to battery memory loss, offered simple storage and transportation, and was more environmentally friendly compared to nickel–cadmium, which is a highly toxic metal (Linden & Reddy 2001).

Nimh was, in turn, replaced by the Lithium-ion (Li-ion) battery which was launched in early 1991. Li-ion batteries have a number of advantages over Nimh batteries. Nimh has a relatively limited service life: performance starts to deteriorate after 200–300 charge/discharge cycles. Nimh also has a relatively short storage life. The Li-ion battery offers higher electrochemical potential, and even today has the largest density for weight of all currently available options (van Schalwijk & Scrosati 2002). What is more, the Li-ion battery is a low maintenance design, i.e. there is no memory discharge, a low self-discharge rate, and no requirement for prolonged priming when new.

Li-ion batteries have their drawbacks. They are expensive to produce compared to other battery types. Also, there were some well documented problems of early versions exploding due to instability of the lithium metal. Temperatures, particularly during charging, could quickly rise to the melting point of metallic lithium, resulting in a violent reaction. The problem was solved by substituting non-metallic elements. One disadvantage that remains is battery ageing. Li-ion batteries typically need replacing after 2 to 3 years, and so are environmentally unfriendly.

Another notable development pushed by the internal logic of the clamshell design was new pointing devices built-in to the base unit. Liberation from desktop use required an alternative to the external mouse. The trackpoint was first introduced on the IBM ThinkPad in 1992. Developed by Ted Salker, this is a small, rubberized button (approximately \(\frac{1}{4}\) inch in diameter) that is located between the ‘G’, ‘H’, and ‘B’ keys on a QWERTY keyboard. The user nudges it in any direction to move the cursor around the screen. Trackpoints were soon offered by a number of clamshell manufacturers, such as Toshiba, HP, NEC, Fujitsu, Acer, and Dell. The touchpad (also known as a trackpad) was first introduced in May 1994 on the Apple Powerbook.

\textsuperscript{7} A recent example was the recall of 10 million under specified Sony batteries in October and November 2006. The catastrophic consequences of an overstressed battery in a laptop can be seen at <http://www.engadget.com/2006/11/14/the-stages-of-an-exploding-laptop-battery/>.
The touchpad is typically located on the base below the keyboard on the base. It has a specialized surface that can translate the motion and position of a user’s fingers to a relative position on screen. Following their introduction, touchpads quickly became a common feature on clamshell portables.\(^8\)

An important development for reducing weight and managing battery power was the replacement of 3 ½ inch hard disk drives by 2 ½ inch drives. Developed by PrairieTek in 1988, all portable manufactures were using 2 ½ inch drives by the early 1990s. By contrast, personal computer designs continue to use 3 ½ inch drives to this day. A comparison of 3 ½ inch and 2 ½ inch drives is provided in Table 1. The large saving in weight which is possible with 2 ½ inch drives is notable. Also notable is the effect of improved technology on the capacity of the listed 2 ½ inch drives. The 64 Mb Conner 2064 was introduced in 1990 and weighs 190 grams. The 815 Mb Toshiba HDD2517 was introduced in 1994 and weighs 143 grams.

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Insert Table 1 about here
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Product innovation also focused on ameliorating the weaknesses of the clamshell design. Thermal management is problematic in desktop personal computers. In clamshells it is major headache because housing the microprocessor in a narrow base unit raises serious thermal management problems. What is more, each generation of microprocessors produces more heat. The ongoing process of miniaturization on integrated circuit boards improves clock speed (the rate at which a transistor switches on and off) by shortening the path that an electron needs to travel. Processing power of microprocessors has continued to double approximately every 18 months over the last 40 years (Moore’s Law). The major downside here is the increase in heat per unit area.\(^9\)

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\(^8\) A number of studies have compared the performance of trackpoints and touchpads (Batra, Dykstra, Hsu, Radle, and Wiedenbeck 1998, Sutter and Ziefle 2003 and 2005). These indicate that users are slightly faster at pointing when using the touchpad.

\(^9\) This heat density on a modern microprocessor is the same as the hot plate of an electric stove. As Chris Bishop demonstrated in his 2008 Royal Institute Christmas Lecture, it takes around 5 minutes to cook an egg using the heat dissipated by the circuit board of a modern computer (Lecture 1, at 31:13 mins, available at <http://research.microsoft.com/en-us/um/people/cmbishop/outreach.htm>).
To address the Achilles heel of increasing plate temperatures, designers have developed ever more sophisticated heat sinks and fans. Indeed, the commercial success of the clamshell since the early 1990s has driven the development of low profile, highly efficient fan technologies and related ‘cold plates’, heat sinks, heat pipes, and dissipation fins. Significant improvements in the design science of cooling have enabled impressive strides to be made in cooling systems. Ideally, this would be assisted by the development of bespoke microprocessors for portables. However, the scale of R&D required in semiconductor to development precludes this option. One option that is exploited by laptop manufacturers is to provide lower spec versions of the current generation of microprocessors (which is why processor speeds and the RAM of portable computers invariably tend to be lower than in comparable PCs).

Finally, let us consider the balance that is required in the development of microprocessors and disk drives. Computing power is a complex phenomenon that governs both computer speed and software stability. Computing power depends on interactions between the random access memory (RAM) of a microprocessor and disk drive storage. A computer program requires contiguous working memory. In practice, this is physically fragmented on RAM and may overflow on to disk storage. Memory is managed by ‘virtual memory’, which frees up RAM by identifying areas that have not been used recently and copies them on to the hard disk. The area of the hard disk that stores the RAM image is called a page file. A balanced design requires developments in RAM that are matched by developments in disk drive capacity. The advantage of hard disk memory is that it is cheap (compared to RAM). However, the read/write speed of a hard drive is much slower than RAM and is not as effective at accessing small pieces of data at a time. A design which is overly dependent on virtual memory suffers in terms of performance. In the worse case, there is ‘thrashing’ and the computer grinds to a halt as the operating system constantly swaps information between RAM and hard disk memory.

**HYPOTHESES**

The design frames concept proposes that a core set of product characteristics define a particular product class. The distinguishing ergonomic feature of the clamshell computer is its screen size. If consumers positively value larger screen

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10 An example is the optimization of volumetric airflows and heatsink fin-pitch.
sizes, then one would expect a correlation between price and larger screen sizes. This provides us with a first test hypothesis:

**Hypothesis 1. Consumers pay a positive shadow price for laptops with larger screens**

If this is the case, then there are consequences for other ergonomic features. The most notable is weight. Some of this additional weight is due to the added weight of a larger screen and, because the proportions of clamshell mean increasing screen size increases the overall dimensions of the portable, there is some additional weight due to larger casings. The most significant increase in weight, however, is due to the larger batteries that are required to run larger sized screens. As discussed, screens are the single most demanding component of battery power. A ‘balanced’ clamshell product requires the use of more powerful, heavier batteries in order to run larger, higher resolution screens. If consumers have strong preferences for larger screens then they will be willing to pay more for laptops that contain larger, heavier batteries.

Initially, the proposition of heavier weight seems surprising. After all, technological downscaling in microprocessors and storage media means their contribution to weight is decreasing over time. Laptop weight therefore provides a useful test of the decoupling of the ergonomic features and the technology features of portable computers. If consumers have strong preferences for lightness, as facilitated by the downscaling of microprocessors every 18 months, then the estimated shadow price for weight will be negative. If, as we propose, a preference for larger screens predominates, then the ergonomics of screen size and weight and inter-correlated, and one would expect a positive shadow price for weight;

**Hypothesis 2. Consumers pay a positive shadow price for heavier laptops.**

The existence of an underlying structure of interactions between the ergonomic and technology characteristics of balanced products leads to a more general proposition. Namely, that there exists in clamshells two distinct clusters of ergonomic features and technological features. This motivates the third test hypothesis;
Hypothesis 3. There is a distinct cluster of interrelated ergonomics characteristics and a distinct cluster of technology characteristics for which consumers are willing to pay positive shadow prices.

DATA SET AND STATISTICAL METHODS

A data set has been collected from information published in the UK consumer magazine WhatPC? in the years 1993 to 1997. WhatPC? is a well known, reputable, and publicly available resource secondary data source. As a data source it offers a number of advantages. First, the data is consistent and complete. Second, the use an independent, publicly available source enables other researchers to access the same information, facilitating replicable results.

This secondary data has been collected for a number of years so that a large sample size available. This ensures sufficient degrees of freedom in the estimated hedonic and principal component methods that will be applied to the data (see below). It is common practice to take observations on products for a (relatively) short period of time and treat them as a single cross section. The short period over which we collect data is 1993 to 1997. In each of these years, the magazine produced an annual ‘Buyers Guide’ listing makes and models, recommended retail prices, and features. There are a total of 921 models listed in the Buyers Guide in the years 1993 to 1997. This number of observations satisfies the data requirements of hedonic price analysis and principal components analysis. What is more, this time period was the heyday of product experimentation amongst clamshell producers. There was a large number competing firms in this period - there are some 129 different manufactures in the data set, and each firm produced models with differentiated product characteristics.

The data set collected using this information contains both ergonomic and technical characteristics. The ergonomic characteristics are:

- \textit{screen} = screen area (length x width in mm),
- \textit{height} = the height of the base unit (mm), and
- \textit{weight} = total laptop eight (kilograms).

The technical characteristics are:

- \textit{clock\_speed} = the clock speed of the microprocessor (megahertz),
- \textit{memory} = its random access memory (bytes),
harddisk = hard disk capacity (bytes),
color_mono = a dummy variable indicating whether the screen is monochrome or color, and
VGA_CGA = a dummy variable indicating whether a CGA or VGA graphics card is loaded.

The data set also contains the dependent variable price (1993) which contains the manufacturer’s recommended retail price for each model. All model prices are deflated using the official UK deflator, with 1993 as the base period.

The data set also includes information on two control variables: year and brand name. Following Chow (1967), hedonic studies of computers include year dummies to control for the Moore’s Law doubling of processing capacity (on circuit boards of a given size and weight) every 18 months. We note that this control variable may also partly pick up the effect of miniaturization in disk drives in the period 1993 to 1997. A second control variable that we consider is brand name. This is useful for identifying brand equity. Aaker (1991) and Keller (1998) propose dominant market firms are able to exploit their brand equity, charging above average prices for products with the same quality of characteristics as their rivals. The proposition has been supported in empirical studies by Keller (1993), Ragaswami, Burke & Ragaswami (1993), Park & Srinivasan (1994), Berndt & Rappaport (2001) and Windrum (2005). We note that this control variable may also pick up some idiosyncratic design aspects that are not captured by the key set of ergonomic and technical characteristics. In order to retain sufficient degrees of statistical freedom, we consider a limited number of leading US, Japanese, and European producers. The following brand name dummies control for brand equity: Acer, Compaq, DEC, Dell, IBM, NEC, Olivetti, Panasonic, Sharp, Tandon, Texas Instruments, Toshiba, and Zenith.

A common problem for empirical studies of product characteristics is that of omitted variables (see Swann 1986). With regards to information on screens, we are fortunate that the data set includes information on both the ergonomics of total area size, and also the relevant technology factors of monochrome / color screens, and graphics cards. It was in the mid to late 1990s that color LCD screen technology became sufficiently affordable that it could be offered on all models. The data set therefore contains monochrome and color models. This enables one to consider the
premium paid for color as a separate factor from screen size. One would also expect positive shadow prices for higher quality video graphics array (VGA) display hardware over lower quality color graphics array (CGA) hardware. There are still a few models in our data set which provided CGA graphics cards. Again, this data enables us to distinguish between the technical aspects of screen quality and their overall size.

We do not have information on battery life in this data set, or battery weight. While the overall weight of laptops is regularly reported by manufacturers and by consumer magazines, battery weight is not normally reported. In order to address, this we have collected our own (primary) data on a small sample of clamshell laptops produced in the early to mid 1990s (Table 2). In this sample, average screen area is 650cm (256 inches), average total weight is 3 kilos (6.6 lbs), and the average battery weight is 0.5 kilos (1.1 lbs). The information in Table 2 indicates that battery weight accounts for a significant proportion of total weight. In this sample, battery weight is between 15% and 20% of total weight.

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Insert Table 2 about here

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Although the size of this small sample precludes statistical testing, a plot of the observations on battery weight and screen area is useful. Figure 2 suggests that a linear or quadratic relationship may exist between these variables.

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Insert Figure 2 about here

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Given this information gleaned from this small sample, we will treat the overall weight of laptops as a proxy for battery weight in our large secondary data set.

Turning to methods, we will estimate a set of hedonic price models to test Hypotheses 1 and 2. Hedonic price regression is the established method for statistically analyzing products in a c-dimensional characteristic space. There is a
synergy between hedonic price regression and the characteristics approach. The characteristics concept underpins the hedonic method of estimating the implicit shadow prices paid for service characteristics (Rosen 1974). The hedonic approach to measuring product innovation has its origins in Court (1939), Stone (1956), Lancaster (1966), and Griliches (1957, 1971).

Under competitive conditions, differences in the prices of rival products reflect quality differences for a common set of product characteristics. Consumers’ revealed preferences are estimated by the shadow prices (the β parameters) that consumers are willing to pay for each characteristic,

\[ p_j = \beta_0 + \sum_i \beta_i \cdot X_{ij} + \varepsilon_j \]  

(1)

where \( p_j \) is the price of the \( j \)th product model; \( \beta_0 \) is a constant; \( \beta_i \) is the estimated coefficient of the relative value which consumers’ place on the \( i \)th product characteristic; \( X_{ij} \) is the level of the \( i \)th characteristic for \( j \)th product; and \( \varepsilon_j \) is the residual.

Hypothesis 3 proposes interrelationships existing among the set of ergonomic and technical characteristics. Curry, Morgan & Silver (2001) observe that omitting interactions between characteristics in equation (1) can lead to misspecified statistical models.

In order to investigate the underlying structure of interactions, we will apply principal components analysis (PCA) and use the estimated components in a hedonic regression. PCA is a well-established statistical procedure for identifying the structure of relationships amongst interrelated variables. There is a well documented literature stretching back to Ahamad (1967, 1968). Compared to other clustering techniques, such as factor analysis, PCA does not make strong prior assumptions regarding the extent and the structure of interdependencies among the original set of variables (Stevens 1992). Another advantage is that one has a clear understanding of the number of \( k \) restrictions that are used to calculate the principal components. PCA assesses the number of composite variables required to achieve a sound representation of the original set of variables. Kaiser and Joliffe criteria retain components that have, respectively, eigenvalues greater than 1 or 0.7. Since, PCA imposes an additional set of linear restrictions on a model, a large number of observations, of around 1000 and upwards, is required.
RESULTS

Estimated Pearson correlation coefficients for price and for the 8 characteristic variables are presented in Table 3, together with descriptive data on the mean average, standard deviation, and minimum and maximum values.

The mean price of £1853.54 ($3707.08) reminds us just how expensive portable computers were in the 1990s. The cheapest listed model in our data set is £330.00 ($660.00) while the most expensive is £6358.88 ($12717.76). The mean average height of the base unit is 0.54 cm (2 inches) and the mean screen area is 652.6 cm (2569 inches). The mean weight is around 3 kilos (6½ lbs), the lightest model being 1 kilo (2 lbs) and the heaviest 9 kilos (20 lbs). Bearing in mind that the original GRiD Compass had a heavy metal case and weighted 11 lbs, it is interesting to observe that some of these later plastic case models are actually much heavier than the first clamshell portable. Still, this needs to be put in context. The Osborne I luggable computer was 20% heavier than the heaviest clamshell computer in our data set.

Both quadratic and linear functional forms of the variables screen size, base unit height, and weight have been assessed. This indicates that linear functional forms for screen and weight are the most appropriate while a quadratic functional form for height is most appropriate. There is a maximum base height/price point beyond which computers with larger base units are sold at lower prices. The estimated quadratic functional relationship between price and height is:

\[ \text{height}_\text{quad} = 271.196 + 36.569 y - 0.105 y^2 \]

estimated Hedonic Price Model for Independent Variables

Table 4 reports the estimated statistical Models 1 and 2. Model 1 includes the dummy year control variable while Model 3 additionally includes the brand name control variable. The estimated coefficients of \textit{screen} and \textit{weight} are positive in both models. This lends support to hypotheses 1 and 2. Consumers are willing to pay a

\[^{11}\] Available from the author, on request.
positive shadow price for clamshells with larger screens. They are also for a positive shadow price for heavier clamshell computers.

The technical characteristics and the remaining ergonomic characteristic of base height (height\_quadratic) take the expected (positive) signs in Models 2 and 3. In both models the estimated coefficients of the characteristic variables are statistically significant at the 1\% level, with the exception of height\_quadratic which is significant at the 5\% level.

Standardized coefficients (z-scores) are reported for Model 2 to facilitate a comparable discussion of the estimated contributions of individual variables to price. The largest relative impact on price is RAM memory: a one standard deviation in memory increases price by £0.35. The relative contributions of the other variables to price are, in order, clock\_speed (£0.30), color\_mono (£0.26), weight (£0.21), harddisk (£0.18), screen (£0.16), and height\_quadratic (£0.07), and VGA\_CGA (£0.04).

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Insert Table 4 about here
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Our third test hypothesis proposes that a ‘balanced product’ implies a particular underlying structure of interactions amongst this set of ergonomic and technology characteristics. As discussed, omitted interactions between the variables raise the issue of model misspecification in Models 1 and 2.

With regards to model specification, the estimated coefficients appear robust when the brand name dummy is added in Model 2. This is positive in that it provides us with some confidence that a key characteristic variable has not been omitted. There is, however, some evidence of inter-correlation amongst the explanatory characteristics variables. The estimated VIF score for harddisk is above the critical value of 5. Also, the variables weight and clock\_speed have VIF scores of 4.255 and 4.474 respectively, just below the critical value. This is suggestive of inter-correlation amongst the explanatory variables producing bias in the regression estimates (see Swann 2006 on this point). This makes a case for applying principal components analysis (PCA) on the data in order to analyse the structure of interactions between the explanatory variables.
Principal Components Analysis and Estimation of Clusters

The findings of the PCA are reported in Table 5. Two orthogonal components are identified in the data set. The first estimated component comprises the technology variables clock_speed, memory, harddisk, and the screen technology variable color_mono. This estimated component accounts for over 38% of the variance across all variables.

The highest values in this component are harddisk (0.926), clock_speed (0.905), and memory (0.872). This high degree of inter-correlation supports our discussion of balanced design amongst these key technology variables.

As important is the fact that color_mono clusters with the other technology variables (0.758) rather than with the ergonomics of screen size. Indeed, a negative value for screen of 0.037 estimated in this component. The technology variable VGA_CGA also clusters with the technology variables, though relatively weakly, with a score of 0.183. Henceforth, we will refer to this first estimated component as the tech component.

The second estimated component comprises the three ergonomic variables of screen, height_quadratic, and weight. This estimated component accounts for 25% of variance across all variables. Henceforth, we will refer to this estimated component as the ergon component.

There are high estimated values for the ergonomic variables in this cluster: weight is 0.96, screen is 0.779, and height_quadratic is 0.70. This indicates that these three variables are strongly orthogonal to the technology variables that make up the tech estimated component. It is notable that both of the screen technology variables color_mono and VGA_CGA take negative signs in this estimated component. This strongly supports the argument that screen ergonomics is distinct to key screen technologies, and that a balanced design is one in which the ergonomics of screen size is inter-correlated with the ergonomics of weight and base unit size.

Taken together, ergon and tech account for 64% of the variance amongst our explanatory variables.

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Insert Table 5 about here
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Turning to the model statistics, the estimated correlation matrix on which the PCA is constructed is within the critical 1% level. The estimated KMO statistic of sampling adequacy is 0.648, well above the critical 0.5 level.

Using these estimated components *ergon* and *tech*, we test Hypothesis 3. For the argument of balanced designs and innovation trajectories to hold, consumers must place a positive shadow price on these clusters of interrelated characteristics. The results of the estimated hedonic price Model 3 are presented in Table 6.

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**Insert Table 6 about here**

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The findings support the hypothesis that consumers place positive valuations on the distinct clusters of design and technical characteristics that make up the clamshell computer design. The coefficients of *ergon* and *tech* take the expected (positive) sign, and both are statistically significant at the 1% level of significance. The estimated standardized coefficients (*z*-scores) are reported for Model 3. A one standard deviation in *tech* increases price by £0.98; a one standard deviation in *ergon* increases price by £0.31.

With regards to collinearity, the VIF scores for *ergon* and *tech* are well below the critical value of 5; *ergon* is 1.125, and *tech* is 3.358. This suggests that the estimated components *ergon* and *tech* address the issue of model misspecification arising from interactions between key independent variables. The results lend further support to the second test hypothesis that clamshell portable contains distinct orthogonal clusters of ergonomic and technological characteristics.

The dummy variables *Compaq, IBM, NEC, Olivetti, Panasonic, Sharp, Texas Instruments, Toshiba*, and *Zenith* are statistically significant at the 1% level, suggesting that other factors are at work. The very well behaved set of VIF results for these control variables (each with a VIF of around 1) is indicative of idiosyncratic product and/or brand premiums rather than missing technology or ergonomic variables with a systematic effect.

Finally, the estimated differentials for *year94, year95, year96*, and *year97* are all significant at the 1% level, and the estimated coefficients are once again consistent with ongoing improvements in microprocessor capacity and in disk drive capacity.
CONCLUSIONS

The paper has sought a more rounded perspective on product innovation; one which places design innovation on a more equal footing with technological innovation. Our theoretical contribution is founded on the concept of the design frame, and an understanding of the way in which designers use design frames in everyday problem solving. Applying Dosi’s work of paradigms to the designer community, we discussed how both design knowledge and technological knowledge fundamentally shapes the trajectory of product innovation by developing the inherent strengths of a design frame while simultaneously addressing its weaknesses. In the case of portable computers, the trajectory of product innovation was set on a very specific path once the clamshell became the dominant design in this market.

The econometric results presented in this paper support the thesis that design and ergonomic characteristics in electronic consumer products are not governed by an underlying set of technological factors or constraints. Technological downscaling due to advances in microprocessors has decoupled many design features from technology. The key feature of the clamshell design is the combination of large sized screens with a QWERTY keyboard interface located on a shallow integrated base unit. As the estimated coefficients for the ergonomic cluster indicate, consumers are willing to pay higher prices for clamshells with larger sized screens, and are willing to accept the commensurate increases in weight (within the range of weight in our data set) that this implies.

The ergonomics of laptop size and weight cannot be explained by developments in microprocessor and disk drive technologies since these lead weight in the opposite direction – i.e. to smaller and lighter devices or, alternatively, to more powerful devices with the same size and weight. The ongoing miniaturization of microprocessors (in line with Moore’s Law) in our data sample was picked up by the estimated differentials of the dummy variables year94, year95, year96, and year97.

Two distinct clusters of ergonomic and technology characteristics were identified by the PCA analysis. These are the two key dimensions along which product innovation develops in this product class. Designers must negotiate trade-offs within these clusters in order to produce a balanced product. Further, as the hedonic results indicate, these two clusters are valued by consumers, indicated by the positive shadow prices estimated for ergon and tech.
The results have important implications for product innovation management. Successful product management requires an understanding of the role(s) of design within innovation, and how the inputs of designers complement and interact with the technological inputs of R&D. The recent success of Apple, outside its traditional computing base, provides a further illustration. In 1997 Apple Corp. was a computer company on the verge of extinction. On 9th July of that year Gil Amelio was ousted as CEO in the wake of a 12 year record low stock price and crippling financial losses. Steve Jobs returned as CEO. Jobs hired Jonathan Ive on the design of the iMAC. Launched in 1998, the shape and translucent plastic body of the integrated a CRT display and CPU of the iMAC placed a new emphasis on product design and aesthetics. Its success bought Apple time to restructure. Ive, who subsequently became Apple’s senior vice-president of design, developed a set of products with distinctive, ergonomic user interfaces which made them instantly recognizable. They include the scroll wheel interface of the iPod (2001), and the touch screen of the iPhone (2007). Apple was not the first to market with its iPod portable media player or its iPhone mobile phone, and rival products have arguably offered superior technical performance. Instead, the competitive advantage of Apple lies in its distinct visual vocabulary, expressed in both product design and advertising. The latter is perhaps most notable in the integrated visual and marketing strategy of its ‘iPod + iTunes’ music business. This extends from the white headphones of the player, to the design of the iTunes website, to advertising featuring a black silhouetted figure holding a white iPod and wearing white earphones against a vibrantly colored background. The commercial success of this strategy has provided Apple with a distinct brand image amongst music consumers who had never previously bought an Apple product.

Of course, the econometric results of our laptop computer study indicate that design-led innovation is not a new phenomenon. Unfortunately, the contribution of design to product innovation has been overlooked in the past. This is an issue which needs to be addressed in future research, particularly research on electronic goods and other product areas in which there is ongoing technological downscaling.

There are important implications here for managers. Technological downscaling in microprocessors and storage media has relaxed the technical constraints on the design and ergonomics for a great many other consumer products. Increasingly, competing goods are distinguishable by their ergonomics, user
interfaces, and other aspects of design. Of course, advances in downscaling technologies continue to play a key role in terms of improving processing power and computational and access speed, but they do not dictate the form or the visible features of rival products. Long term competitiveness requires the bringing together of designers and R&D engineers in the innovation process. This represents a major shift in the management of product innovation, which has long been the preserve of the R&D department. All too often, R&D engineers oppose inputs from industrial designers, even in small design-conscious firms (Moody 1980). Yet the results of our study clearly indicate that designers have much to offer in determining market positioning, understanding and creating demand, and addressing and unlocking the latent needs of consumers. Long term competitiveness requires the strategic harnessing and integration of inputs from designers and R&D engineers.
FIGURE 1
Osborne I, GRiD Compass & GRiDPad 1910.

<table>
<thead>
<tr>
<th>Osborne I</th>
<th>GRiD Compass</th>
<th>GRiDPad 1910</th>
</tr>
</thead>
</table>

![Osborne I](image1)

![GRiD Compass](image2)

![GRiDPad 1910](image3)
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Capacity</th>
<th>Size (cm)</th>
<th>Weight (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seagate ST3660A</td>
<td>3 ½ inch</td>
<td>545.5 MB</td>
<td>10.4 x 13.8 x 1.5</td>
<td>0.470</td>
</tr>
<tr>
<td>IBM OEM DPE5-31080</td>
<td>3 ½ inch</td>
<td>1050 MB</td>
<td>10.4 x 13.8 x 1.5</td>
<td>0.506</td>
</tr>
<tr>
<td>IBM Deskstar NM17951</td>
<td>3 ½ inch</td>
<td>41GB</td>
<td>10.4 x 13.8 x 1.5</td>
<td>0.551</td>
</tr>
<tr>
<td>Conner CP 2064</td>
<td>2 ½ inch</td>
<td>64 MB</td>
<td>19.0 x 7.0 x 1.6</td>
<td>0.190</td>
</tr>
<tr>
<td>IBM DBOA-2540</td>
<td>2 ½ inch</td>
<td>540 MB</td>
<td>11.5 x 7.5 x 2.0</td>
<td>0.204</td>
</tr>
<tr>
<td>Toshiba HDD2517</td>
<td>2 ½ inch</td>
<td>815 MB</td>
<td>10.0 x 7.0 x 1.3</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Source: Items provided by the Centre for Computing History, Haverhill, UK.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Screen area (cm)</th>
<th>Total weight (k)</th>
<th>Battery weight (k)</th>
<th>Battery / Total weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tandon NB/386 SX</td>
<td>611.6</td>
<td>3.147</td>
<td>0.53</td>
<td>0.168</td>
</tr>
<tr>
<td>Sharp PC-6200</td>
<td>616.0</td>
<td>2.814</td>
<td>0.44</td>
<td>0.156</td>
</tr>
<tr>
<td>Toshiba T2450 CT/500</td>
<td>657.9</td>
<td>2.845</td>
<td>0.46</td>
<td>0.162</td>
</tr>
<tr>
<td>AST Premium Exec 386SX</td>
<td>662.4</td>
<td>3.292</td>
<td>0.55</td>
<td>0.167</td>
</tr>
<tr>
<td>Compaq LTE/286</td>
<td>602.0</td>
<td>3.148</td>
<td>0.53</td>
<td>0.168</td>
</tr>
<tr>
<td>Zenith MastersPort 386SX</td>
<td>597.7</td>
<td>3.034</td>
<td>0.50</td>
<td>0.165</td>
</tr>
<tr>
<td>Apple Powerbook 150</td>
<td>684.0</td>
<td>2.667</td>
<td>0.52</td>
<td>0.195</td>
</tr>
<tr>
<td>NEC Versa S/33</td>
<td>577.5</td>
<td>1.887</td>
<td>0.32</td>
<td>0.170</td>
</tr>
<tr>
<td>Toshiba T1860</td>
<td>625.8</td>
<td>3.192</td>
<td>0.51</td>
<td>0.160</td>
</tr>
<tr>
<td>Apple Powerbook 165C</td>
<td>662.7</td>
<td>3.224</td>
<td>0.53</td>
<td>0.164</td>
</tr>
<tr>
<td>Apple Powerbook 180</td>
<td>662.7</td>
<td>3.180</td>
<td>0.53</td>
<td>0.167</td>
</tr>
<tr>
<td>IBM Thinkpad 755CE</td>
<td>617.4</td>
<td>2.893</td>
<td>0.48</td>
<td>0.166</td>
</tr>
<tr>
<td>Commodore C286-LT</td>
<td>790.5</td>
<td>3.009</td>
<td>0.48</td>
<td>0.160</td>
</tr>
<tr>
<td>Zenith MastersPort 386SLe</td>
<td>661.5</td>
<td>3.226</td>
<td>0.53</td>
<td>0.164</td>
</tr>
<tr>
<td>Toshiba Satellite 200CDT/810</td>
<td>705.0</td>
<td>3.525</td>
<td>0.57</td>
<td>0.162</td>
</tr>
</tbody>
</table>

Average: 650.0 3.006 0.50 0.166

Source: Items provided by the Centre for Computing History, Haverhill, UK.
FIGURE 2

Plot of battery weight and screen area of small sample of portables

Battery_weight

Model Summary and Parameter Estimates

<table>
<thead>
<tr>
<th>Equation</th>
<th>Model Summary</th>
<th>Parameter Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R Square</td>
<td>F</td>
</tr>
<tr>
<td>Linear</td>
<td>.129</td>
<td>1.927</td>
</tr>
<tr>
<td>N=15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The independent variable: Screen_area.
### TABLE 3
Medians, Means, Standard Deviations & Pearson Correlation Coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Median</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Min.</th>
<th>Max.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. price (1993)</td>
<td>1604.38</td>
<td>1853.54</td>
<td>914.29</td>
<td>330.00</td>
<td>6358.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. screen</td>
<td>63248.64</td>
<td>65260.00</td>
<td>12903.042</td>
<td>5700.00</td>
<td>148931.60</td>
<td>.299***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. height</td>
<td>50.80</td>
<td>53.56</td>
<td>26.10</td>
<td>4.80</td>
<td>355.60</td>
<td>.283***</td>
<td>.325***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. weight</td>
<td>2.90</td>
<td>3.08</td>
<td>1.05</td>
<td>1.00</td>
<td>9.00</td>
<td>.364***</td>
<td>.708***</td>
<td>.745***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. clock_speed</td>
<td>50.00</td>
<td>55.35</td>
<td>33.79</td>
<td>8</td>
<td>200</td>
<td>.346***</td>
<td>-.073**</td>
<td>-.031</td>
<td>-.044*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. memory</td>
<td>4096000.00</td>
<td>5362711.07</td>
<td>3307999.01</td>
<td>1024E3</td>
<td>32768E3</td>
<td>.453***</td>
<td>-.090***</td>
<td>-.034</td>
<td>-.039</td>
<td>.718***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. harddisk</td>
<td>2.05E8</td>
<td>3.09E8</td>
<td>3.065E8</td>
<td>1024E3</td>
<td>2048E6</td>
<td>.408***</td>
<td>-.047*</td>
<td>-.015</td>
<td>-.009</td>
<td>.820***</td>
<td>.791***</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. color_mono</td>
<td>.00</td>
<td>.45</td>
<td>.50</td>
<td>0</td>
<td>1</td>
<td>.384***</td>
<td>-.057**</td>
<td>-.008</td>
<td>-.031</td>
<td>.601***</td>
<td>.516***</td>
<td>.592**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9. VGA_CGA</td>
<td>1.00</td>
<td>.99</td>
<td>.10</td>
<td>0</td>
<td>1</td>
<td>.113***</td>
<td>.033</td>
<td>.014</td>
<td>.045*</td>
<td>.119***</td>
<td>.117***</td>
<td>.090**</td>
<td>.089**</td>
<td>1</td>
</tr>
</tbody>
</table>

N = 921

*** p<.01
** p<.05
* p<.10
## TABLE 4
Estimated Hedonic Price Models 1 and 2 for Ergonomic & Technical Characteristics with Control Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 1 Coefficient</th>
<th>S.E.</th>
<th>VIF</th>
<th>Model 2 Coefficient</th>
<th>S.E.</th>
<th>Standized Coefficient</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>screen</td>
<td>.012***</td>
<td>(.003)</td>
<td>2.690</td>
<td>.011***</td>
<td>(.003)</td>
<td>.156</td>
<td>2.747</td>
</tr>
<tr>
<td>height_quadratic</td>
<td>.010**</td>
<td>(.004)</td>
<td>2.108</td>
<td>.009**</td>
<td>(.004)</td>
<td>.067</td>
<td>2.121</td>
</tr>
<tr>
<td>weight</td>
<td>135.930***</td>
<td>(41.186)</td>
<td>4.151</td>
<td>183.398***</td>
<td>(38.903)</td>
<td>.210</td>
<td>4.255</td>
</tr>
<tr>
<td>clock_speed</td>
<td>6.939***</td>
<td>(1.331)</td>
<td>4.362</td>
<td>8.331***</td>
<td>(1.258)</td>
<td>.303</td>
<td>4.743</td>
</tr>
<tr>
<td>memory</td>
<td>9.843E-5***</td>
<td>(1.130E-5)</td>
<td>2.884</td>
<td>1.000E-4***</td>
<td>(1.061E-5)</td>
<td>.348</td>
<td>2.919</td>
</tr>
<tr>
<td>harddisk</td>
<td>8.986E-7***</td>
<td>(1.628E-7)</td>
<td>4.880</td>
<td>5.924E-7***</td>
<td>(1.571E-7)</td>
<td>.186</td>
<td>5.223</td>
</tr>
<tr>
<td>color_mono</td>
<td>556.857***</td>
<td>(56.273)</td>
<td>1.730</td>
<td>479.349***</td>
<td>(53.329)</td>
<td>.260</td>
<td>1.785</td>
</tr>
<tr>
<td>VGA_CGA</td>
<td>413.416***</td>
<td>(220.011)</td>
<td>1.038</td>
<td>339.793***</td>
<td>(206.709)</td>
<td>.036</td>
<td>1.052</td>
</tr>
</tbody>
</table>

| Control Variables:      |                     |       |      |                     |       |                      |      |
| year94                  | -170.551**          | (71.246)| 1.661| -155.381**         | (66.621)| -.065                 | 1.668|
| year95                  | -409.007***         | (72.824)| 1.945| -388.878***        | (68.453)| -.173                 | 1.974|
| year96                  | -1085.164***        | (89.741)| 2.998| -1023.909***       | (84.198)| -.458                 | 3.032|
| year97                  | -1651.843***        | (121.337)| 4.973| -1497.767***       | (114.505)| -.638                 | 5.088|
| Acer                    |                      |       |      |                     |       |                      |      |
| Compaq                  | 325.547***          | (123.368)| .58  | 314.124***         | (247.812)| .028                 | 1.011|
| DEC                     | 314.124             | (247.812)| .028|                     |       |                      |      |
| Dell                    | 14.039              | (153.170)| .002|                     |       |                      |      |
| IBM                     | 877.624***          | (111.917)| .173|                     |       |                      |      |
| NEC                     | 491.318***          | (170.008)| .063|                     |       |                      |      |
| Olivetti                | 329.987***          | (108.475)| .067|                     |       |                      |      |
| Panasonic               | 776.704***          | (156.402)| .111|                     |       |                      |      |
| Sharp                   | 808.546***          | (216.043)| .082|                     |       |                      |      |
| Tandon                  | 480.027             | (349.739)| .030|                     |       |                      |      |
| Texas Instruments       | 532.271***          | (112.236)| .105|                     |       |                      |      |
| Toshiba                 | 543.312***          | (97.655)| .124|                     |       |                      |      |
| Zenith                  | 399.623***          | (126.645)| .069|                     |       |                      |      |

| Constant                | -553.567***         | (243.742)|       | -681.054***        | (229.394)|       |       |

| N                       | 921                 |       | 921          |       |                      |      |
| F                       | 79.602              |       | 49.813      |       |                      |      |
| Adjusted R²             | .507                |       | .571        |       |                      |      |
| Res. Sum                | 3.767E8             |       | 3.232E8     |       |                      |      |

* Uncorrected standard errors in parentheses.
<table>
<thead>
<tr>
<th>Variables</th>
<th>Retained Principal Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>screen</td>
<td>-.037</td>
</tr>
<tr>
<td>height_quadratic</td>
<td>.006</td>
</tr>
<tr>
<td>weight</td>
<td>.021</td>
</tr>
<tr>
<td>clock_speed</td>
<td>.905</td>
</tr>
<tr>
<td>memory</td>
<td>.872</td>
</tr>
<tr>
<td>harddisk</td>
<td>.926</td>
</tr>
<tr>
<td>color_mono</td>
<td>.758</td>
</tr>
<tr>
<td>VGA_CGA</td>
<td>.183</td>
</tr>
</tbody>
</table>

Number of Observations

|                         | 921  | 921  |

Eigenvalues:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3.075</td>
<td>2.009</td>
</tr>
<tr>
<td>% of Variance</td>
<td>38.436</td>
<td>25.107</td>
</tr>
<tr>
<td>Cumulative % of Variance</td>
<td>38.436</td>
<td>63.544</td>
</tr>
</tbody>
</table>

Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy 0.648
Bartlett’s test of sphericity: Approximate Chi-Square 3760.827
   DF:28
   Sig.: 0.000

Rotation Method: Varimax with Kaiser Normalization.
Rotation converged in 3 iterations.
TABLE 6
Estimated Hedonic Price Model 4 for Ergonomic & Technical Principal Components with Control Variables


<table>
<thead>
<tr>
<th>Variables</th>
<th>Model 3</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>S.E.</td>
<td>Standardized Coefficient</td>
<td>VIF</td>
</tr>
<tr>
<td>ergon</td>
<td>279.937***</td>
<td>(21.185)</td>
<td>.305</td>
<td>1.125</td>
</tr>
<tr>
<td>tech</td>
<td>898.119***</td>
<td>(36.603)</td>
<td>.978</td>
<td>3.358</td>
</tr>
</tbody>
</table>

Control Variables:

| year94     | -172.362*** | (66.374) | -.072    | 1.636    |
| year95     | -426.320*** | (67.384) | -.189    | 1.890    |
| year96     | -1076.643***| (79.888) | -.481    | 2.696    |
| year97     | -1579.554***| (107.554)| -.673    | 4.435    |

| Acer       | 151.860     | (153.413) | .022     | 1.010    |
| Compaq     | 315.425**   | (123.656) | .056     | 1.015    |
| DEC        | 310.866     | (248.836) | .027     | 1.008    |
| Dell       | -12.576     | (153.891) | -.002    | 1.016    |
| IBM        | 864.524***  | (112.209) | .170     | 1.030    |
| NEC        | 483.983***  | (169.878) | .062     | 1.010    |
| Olivetti   | 337.557***  | (108.435) | .068     | 1.021    |
| Panasonic  | 758.981***  | (155.062) | .108     | 1.032    |
| Sharp      | 849.905***  | (216.055) | .086     | 1.011    |
| Tandon     | 458.906     | (351.485) | .029     | 1.008    |
| Texas      | 484.126***  | (111.871) | .095     | 1.023    |
| Instruments|          |          |          |          |
| Toshiba    | 519.123***  | (97.103)  | .118     | 1.032    |
| Zenith     | 352.485***  | (126.257) | .061     | 1.017    |

| Constant   | 2373.984*** | (58.277)  |          |          |

N 921
F 63.870
Adjusted R² .565
Res. Sum 3.293E8

Squares

*** p<.01
** p<.05
* p<.10

Uncorrected standard errors in parentheses.
REFERENCES


